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Numerical Simulation Study on Sprinkler Control Effect in UBS Fuel Tank Room of Nuclear Power Plants

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Abstract

FDS (Fire Dynamics Simulator) is the software to computing fluid dynamics which taking the flowing in fire as the main simulation target. In this paper, a model closed to real fire scenario of UBS (emergency diesel generator) fuel tank room of NPP is established by FDS. By analyzing this model, details on the effectiveness of controlling the fire source heat release rate, the key point temperature and the slices in the process of fire extinction based on sprinkler systems are discussed. In addition, it will show the advantages and feasibilities of FDS in NPP(nuclear power plant) application.

Keywords: FDS, NPP, Fire protection, Sprinkler effect

Nomenclature

m_f	mass loss rate($kg \cdot m^{-2} \cdot s^{-1}$)
m''_∞	maximum mass loss rate($kg \cdot m^{-2} \cdot s^{-1}$)
k	flame attenuation factor
Q	heat release rate in the unit area of combustible materials（$kw \cdot m^{-2}$）
H	combustion heat of liquid ($kg \cdot m^{-2}$)
Greek symbols	
β	the average light-length correction factor
η	combustion efficiency

1. Introduction

UBS fuel tank rooms of NPP are the places which are suffer from high frequency of fire accidents and when the fire accident occurred, it would be hard to controlled put out. High radiation made by the swift and violent fire which do harm to equipments and tanks nearby may expand the fire disaster. On the other hand, if the fire in fuel tank room touched operation

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functional area in NPP, the condition of reactor will be changed, as well as increasing the risk of the safety of nuclear.Based on this discussion, study on fire hazard in UBS fuel tank rooms is an important subject in NPP fire protection.

In China, studies on fire in UBS fuel tank room of NPP are relatively late, while methods and technology are backward. The second generation improved nuclear power project, which is mainly being used in China, is using a set of manual calculation methods introduced by France. The method is based on normalized thermal program. This program can get the time of the fire lasting in fire district by calculating fire load densities, and then compare with fire resistance of boundary, which cannot get the actual situation of temperature rise in fire and describe the control effect of sprinkle system. Consequently, there are some limitations in this method and technology [1].

In this study, a model closed to real fire scenario of UBS Fuel Tank Room is established in NPP, and details on the effectiveness of controlling the fire source heat release rate, the key point temperature and the slices in the process of fire extinction based on sprinkler systems are discussed. In addition, it will show the advantages and feasibilities of FDS in NPP application.

2. FDS fire modeling

2.1. Introduction of calculation model

FDS is a three dimensional computational fluid dynamics software (CFD), developed by NIST (National Institutes of Standards and Technology) and BFRL (Building and Fire Research Laboratory), based on large eddy simulation (LES), simulating the process of turbulence flowing in fires. FDS solves numerically a form of the Navier-Stokes equations appropriate for low speed, thermally-driven flow with an emphasis on smoke and heat transport from fire [2-4].

2.2. Parameter setting of fuel tank room

The calculation region of fuel tank room is a cuboid's space with 10m×8m×4m. The building structure is reinforced concrete materials with a wall thickness of 0.5m. The fuel tank is located in the middle of the region in 8m×2m×2m, and the fuel is diesel. The releasing stresses of spray system are 0bar, 0.5bar, 1.0bar and 2.0 bar respectively, the increasing coefficients (K-factor) is 40L/min/bar$^{1/2}$, while the responsive temperature is 74℃. It's setted as a square and the intervals are 2m and 3m respectively, the environment temperature is 20℃. The calculation region of fuel tank room is shown in Fig. 1.

And parameter settings of simulating in FDS calculation region are shown in Table 1.

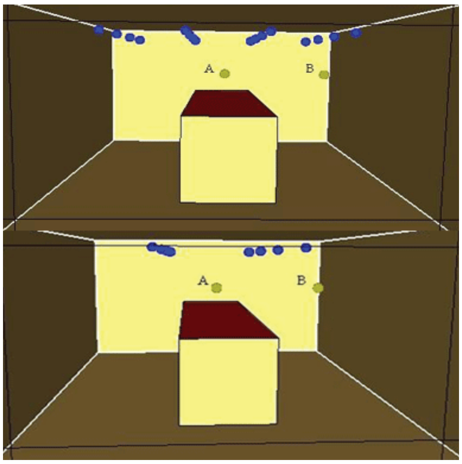

Fig. 1. The calculation region of fuel tank room

2.3. Setting the parameters of fire source

2.3.1 Combustion mass loss rate of oil pool

The type of fire in fuel tank room of NPP underground is usually pool fire, the combustion mass loss rate in the combustion process [5] is:

$$m_f = m''_\infty (1 - e^{-k\beta D}) \qquad (1)$$

For the diesel, Munoz [6] and others obtained the numbers of m''_∞ and $k \cdot \beta$ by experiment, m''_∞ =0.062m^{-1} and $k \cdot \beta = 0.63\text{m}^{-1}$ through experiments. Inserting them into formula (1), the result of m''_∞ is 0.062.

Table 1. Parameter settings of simulating

type	parameter	value
1	spatial dimension	10m×8m×4m
2	lattice distribution	55×45×25
3	material of wall	reinforced concrete
4	thickness of wall	0.5m
5	releasing stress	0bar/0.5bar/1.0bar/2.0bar
6	response temperature	74℃
7	K-Factor	40
8	flow velocity of droplets	5m/s

2.3.2 Heat release rate in the unit area

In FDS, the size of fire source is set by calculating the heat release rate in the unit area of combustible materials [7]:

$$Q = \eta H m_f \qquad (2)$$

The combustion efficiency of diesel ranges from 0.68 to 0.85, the value of η is 0.8. Then calculate the heat release rate in the unit area is2060kw$\cdot$m^{-2}. In combustion process, fire development coefficient of diesel is 0.16. Basis for t^2 [8] model that heat release rate changing with time, number the time reaching the maximum heat release rate as 105s.

According to the differences of spray locations and releasing stresses in fuel tank room, different fire scenes simulated, which are shown in Table 2.

Table 2. Numerical simulation of fire scenes

Fire Scene	Heat Release Rate in the Unit Area (kW/m^2)	Spray Distance (m)	Releasing Stress (bar)
Case 1	2060	-	-
Case 2	2060	2	0.5
Case 3	2060	2	1.0
Case 4	2060	2	2.0
Case 5	2060	3	0.5
Case 6	2060	3	1.0
Case 7	2060	3	2.0

3. Results and discussions

3.1. The change of heat release rate

3.1.1 The change of heat release rate by spray distance

The simulation process is divided into two conditions: with spraying and without spraying. The comparison about the heating release rates in different sprinkler distance under 1.0 bar is made between the condition with spraying and without spraying, as Case 1/2/6 shown in Table 2.

Fig.2 shows that the heat release rate of fire source has no obvious change at the initial stages of the combustion. At 50s, the heat release rate of fire source in calculation region under spray began decaying. At the same time, the fire was effectively controlled by sprinkler system, and the control effects will be increased with the sprinkler distance decreasing.

3.1.2 The change of heat release rate by sprinkler pressure

Fig.3 shows the changing of heat release rates of fire source in different sprinkler pressure against time when sprinkler distance is 2.0m.

At 50s, the fire was controlled by sprinkler system effectively, and the control effects are better when sprinkler pressure is increasing. When the spray pressure is reached 2.0 bars, the fire will be cooled and quenched deeply.

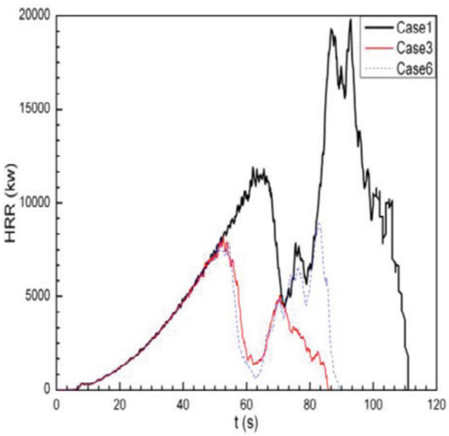

Fig. 2. The change of heat release rate in different sprinkler distances

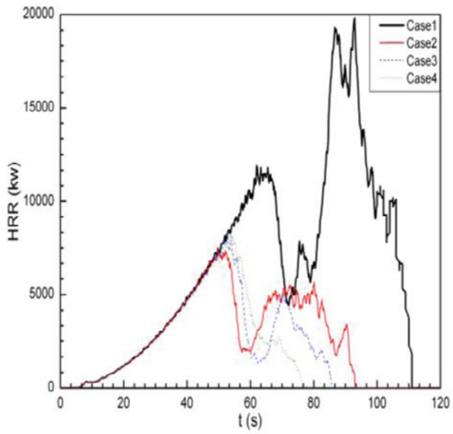

Fig. 3. The change of heat release rate in different sprinkler distances

3.2. The change of key point and section temperature

Main mechanism of sprinkler system is to decrease the temperature in fire scene to critical temperature of fire extinguishing. Two key points are selected to analyze the control effects of sprinkler system in different temperature, which point A is directly located 0.8m above the center of fire source, and point B is located at the right of point A 3.0m.

3.2.1 The change of temperature at point A

Fig.4 shows the changing of temperature from 0s to 140s at point A. There is little difference in the first 50 seconds. After 50s, under the impact of sprinkler system temperature at point A has been controlled effectively, drops reach point A through smoke. Comparing with situation without sprinkler, the temperature decreases 65% when the spray pressure reaches 0.5 bars. But the differences of temperature are not much at this point in different sprinkler pressures. As a consequence, the decrease amplitude at point A is obvious substantially, thus point A is the covering dot by droplets.

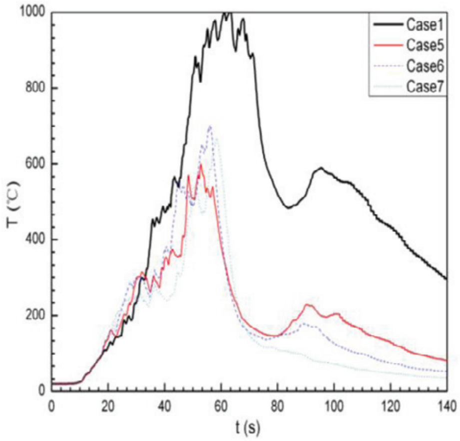

Fig. 4. Temperature under different sprinkler pressures in 3.0m separation distance at point A

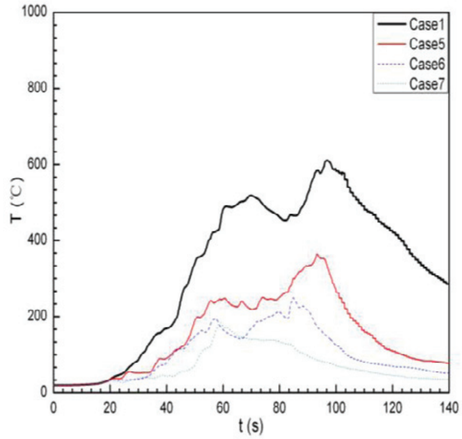

Fig. 5. Temperature under different sprinkler pressures in 3.0m separation distance at point B

3.2.2 The change of temperature at point B

As shown in Fig.5, at point B the maximum temperature reached 611℃ without sprinkler. When the sprinkler pressures are 0.5bar, 1.0bar and 2.0bar respectively, the contribution rates of sprinkler to low the temperature are 45%,76% and 87%.Point B locates at smoke layer where pressure is higher because of ceiling jet, so that droplets can't get through smoke layer effectively without increasing sprinkler pressure to cool the flame.

3.2.3 The change of slice temperature

Measuring temperature in Slices is also an important method to get simulated result. In this process, we select two Slices, one in Case1 and another in Case5, perpendicular to the surface and including point A and B.

Fig.6 shows that at 65s, the temperature right above fire source without sprinkler (a) reached 700℃. When sprinkler system with 3m separation distance and 0.5 bar sprinkler pressure is put into use (b), the temperature could be controlled in 450℃. It's confirmed that sprinkler system plays an important role in decreasing the temperature in the coverage area.

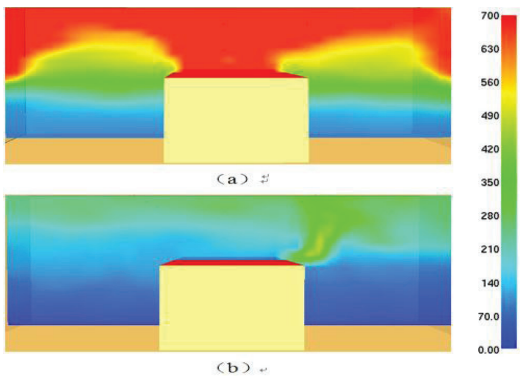

Fig. 6. Temperature in slices right above fire source

4. Conclusions

This work based on the FDS has established a set of close to true fire scenario of UBS fuel tank room of NPP, and studied the control effect for fire in different distances and different sprinkler pressures. Simulation results indicate that when the sprinkler system pressure release for 1 bar, spacing for 2.0 m and 3.0 m, the sprinkler system can have a cooling effect on fire, which reducing the heat release rate to effectively controlling the fire and better for fire control with the sprinkler spacing of the reduction of the sprinkler system. In particular sprinkler spacing, increasing the release pressure can get more droplets kinetic energy and more effectively to fire the surface to reduce the ignition heat release rate.

From the change of temperature for point A to get the result that in the droplets coverage of the area, the temperature is reduced when the droplets get through the layer, at the same time the effects of sprinkler pressure is no longer apparent.

From the change of temperature for point B, it can be noticed that the smoke rise to the ceiling is affected by the ceiling jet, and increasing the pressure of the sprinkler release if the position is away from the fire source to make the droplets through the smoke layer and get cool.

It is seen from the slices of different sprinkler pressure at 65s that the temperature above the fire source is reduced with the opening of the sprinkler system. It is effect to the temperature weakening by sprinkler system within coverage area.

Based on the particularity of the structure of NPP, it is difficult to do an entity experiment on the researching on the fire in NPP fuel tanks rooms. According to the real environment situation of the scene, relatively credible fire load and the model of the distribution for the fire source were set up. By FDS simulation, it’s able to calculate the real situation of the fire temperature rising, as well to describe the effect of sprinkler system in controlling the fire. From the point of nuclear safety review, the way of fire evaluation will be changed, and more useful references for NPP fire protection will be provided by FDS.

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